THE ORIGIN AND DEVELOPMENT OF LIMESTONE CAVES: A GENERAL SURVEY

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INTRODUCTION

Caves are natural cavities in the ground. A cave can be as small as a few feet or can extend for miles. Caves can be formed by streams in glacial ice, deposition of large amounts of talus, and coastal wave action but the majority ~~if~~ of caves were formed by the solution of limestone and other solu~~a~~ble rocks. There are also extensive lava caves (Sloane 1977). Terrain with distinctive drainage and land forms developing from rock having greater solubility in natural waters than elsewhere is termed karst. Solution is not always the most prevelant or most dominant karst process but it does play an important role in karst landscape development. The most critical effect is the enlargement of underground voids causing increased permeability of the rock. This leads to the progressive replacement of surface drainage with underground drainage (Jennings 1985).

Caves, and the structures within them, are the most well known karst features. Essentially, caves are conduits for the transport of solutes and water. These conduits generally form along lines of weakness in rock such as joints and bedding planes. Conduit development is controlled by intrinsic properties of the rock including: porosity, permeability, composition, and hydraulic conductivity; and external factors such as climate, hydraulic gradient, and water circulation patterns of the area. In general, the greater the circulation of water the greater the solution of the rock.

Limestone caves form as the surface drainage flow path is diverted to the underground through fissures, joints and bedding planes. The limited porosity of limestone leads to solutional enlargement of flow cavities. Integrated flow networks consisting of water filled passages cause the dissolution of the rock to form caves, or an underground space. The size of the space is relative and no size restriction has been given to the term "cave" however, observation and description are limited by the accessibility of the cavity.

The many features of cave forms are developed by two main processes. First, the solution of the limestone and second, the deposition of material into the space by breakdown or precipitation. W. M. Davis (1930) referred to these processes as cycles. A one-cycle cave is a cavity of solutional or corrasional excavation (Davis 1930) without any depositional features. Those cavities containing passages and voids as well as depositional features (stalactites, stalagmites, curtains, etc.) are referred to as two-cycle caves.

For karstification to develop and for solution to form caverns it is necessary; 1) that water rich in CO_2 is available to recharge the system, 2) that sufficient permeability of fractures be available for water to circulate in the rocks, 3) that water be able to discharge from the system. Structures and tectonics are responsible for displacing carbonate rocks from their depositional environment and exposing them to an environment conducive to karstification. The most significant of the structural and tectonic influences of karstic features is uplift. The three main catagories of uplift are: 1) the gently raised plain--lowering of sealevel or slight tectonic action; 2) a great uplift--tectonic elevation high above sealevel; 3) arching and erosion of clastic cover--tectonic uplift producing arching or anticlinal structure (Ford 1971). Examples of the arching type are the Ozarks of Missouri (Powell 1953) and the Kentucky Karst Region (Viresay 1953). Diamond Caverns in Kentucky exemplifies the gently raised plain (McGrain 1961). Carlsbad Caverns, New Mexico were faulted and tilted (Sloane 1977).

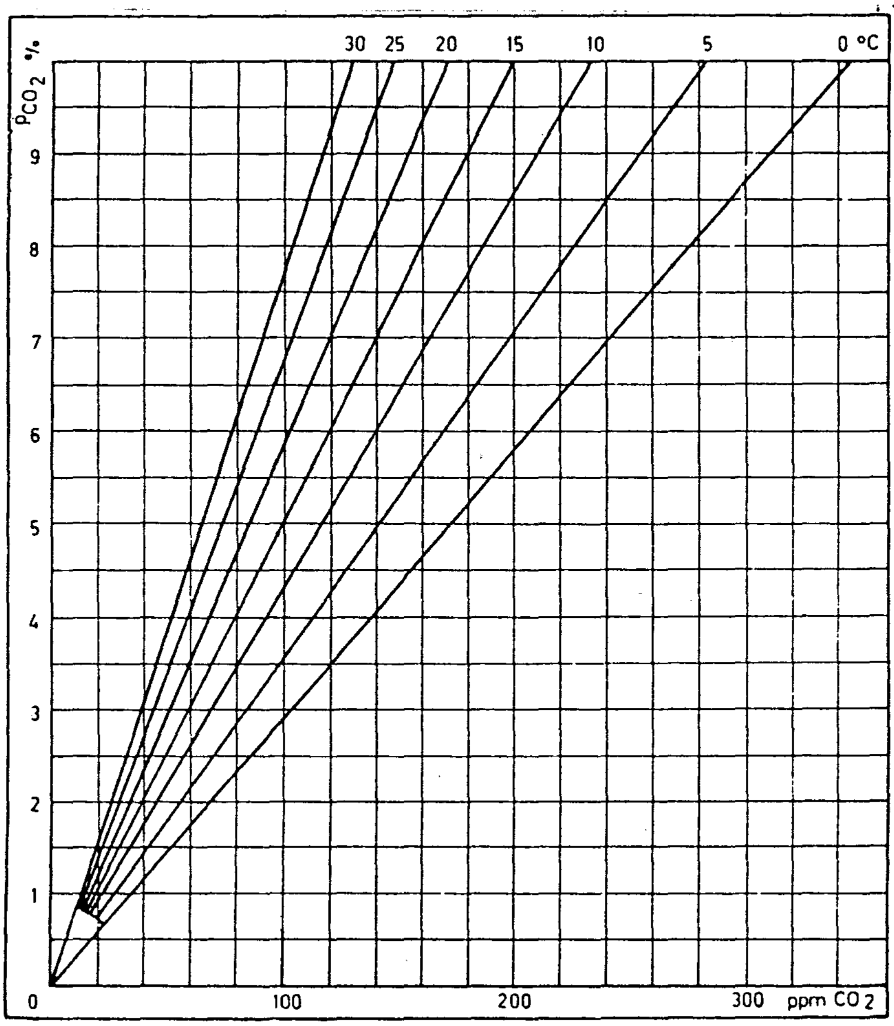
SOLUTION OF LIMESTONE

The development of caves and caverns in limestone begins with the circulation of water within the limestone rock body and the various accompanying chemical reactions. The porosity of a limestone varies with its lithologic characteristics. High porosity and permeability lead to more uniform flow through the rock. This makes the presence of joints less important to water flow. Low permeability acts to focus water flow along joints and fissures increasing the effects of erosion. The extent of the solution is largely due to the number, frequency, and interconnectedness of the fractures, fissures, and bedding planes. These penetrable joints and bedding planes provide percolating water access to the rock surface. The surface area available for corrosion increases with the porosity and permeability of the limestone. Permeability in limestone is largely developed by the circulation of the subsurface water. This causes a loss of interstitial porosity and the creation and enlargement of joints by solution.

Although pure water is only capable of dissolving 13mg/L of calcite at 16C and 15mg/L at 25C (Jennings 1985), the calcite of limestone is more soluble in water containing CO_2 (Davis 1930). Subsurface water is charged with CO_2 as it mixes with the atmospheric CO_2 and organic soil layers. The amount of CO_2 that may be dissolved in water increases with increasing atmospheric pressure and decreasing temperature (Fig. 1).

FIGURE 1.

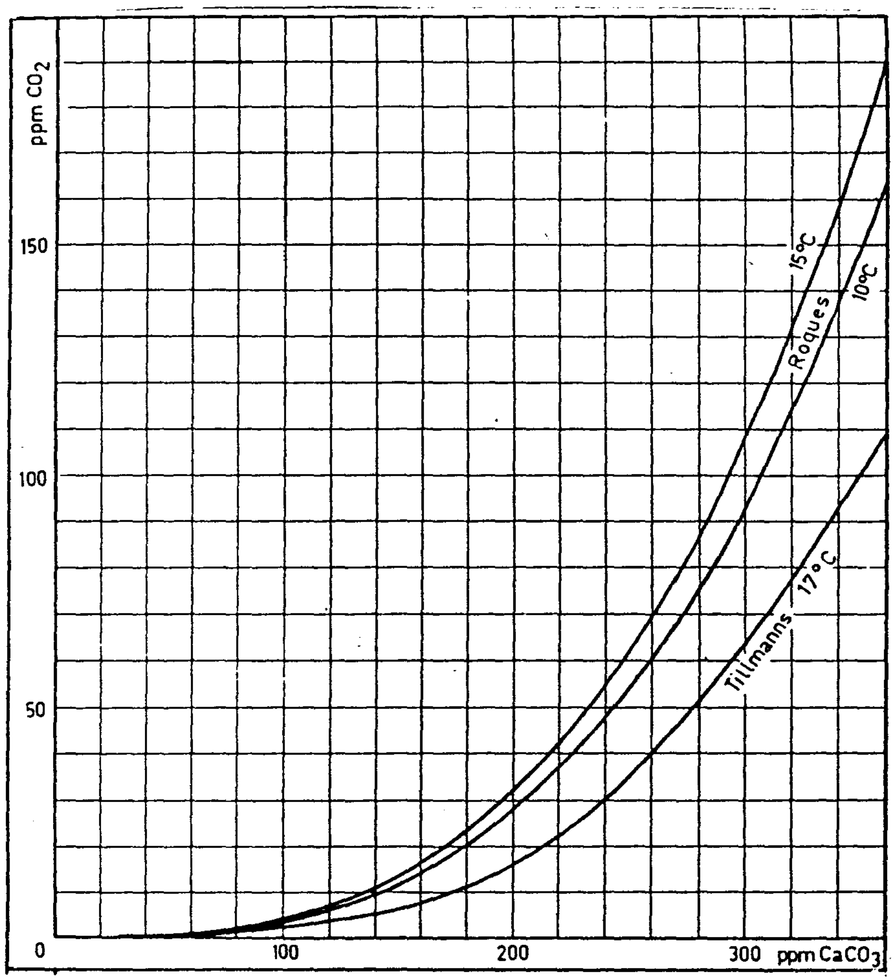
Partial Pressure of CO2(0-9%) vs. Dissolved CO2(ppm)



Hence the solubility of limestone increases with increasing atmospheric pressure and decreasing temperature (Fig. 2).

FIGURE 2.

The Dissolution of CACO3 as Dependent on the Concentration of CO2 (Bogli 1980).



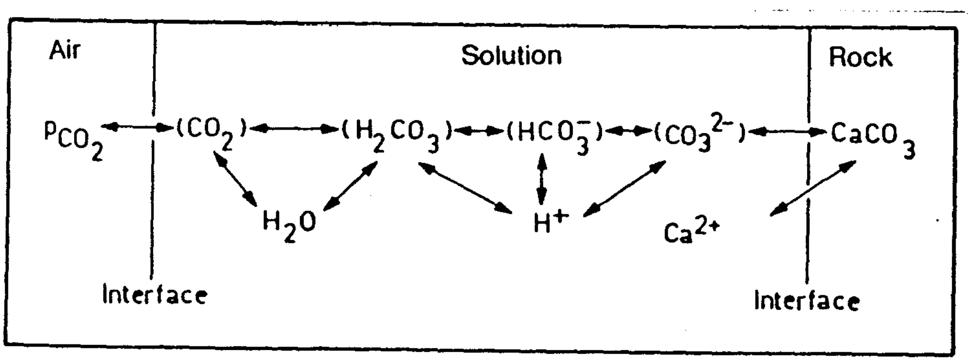
Concentrations of CaCo3 are greater in natural waters than in pure water due to the presence of dissolved acids in the natural waters. Most important of these acids is carbonic acid.

The main source of carbonic acid is atmospheric carbon dioxide. Other sources are root respiration and bacterial decay of organic matter. Other acids capable of attacking limestone are organic acids and sulphuric acid. Organic acids are obtained from rotting vegetation, peat bogs, and peaty waters. Sulfuric acid is also formed in bogs as a result of bacterial action and the weathering of sulfide minerals such as pyrite. Most of the dissolved acids are incorporated into the water chemistry close to the surface or just beyond the surface in the soil zone However, the mixing of brine and fresh water occurs below the soil zone in the saturation zone (Bogli 1980).

The dissolution of limestone includes both physical reactions and chemical reactions. Carbon dioxide is found in solution, even in rainwater, and since some water is always in dissociated state, slow reactions to form carbonic acid are continual. Carbonic acid then, also exists in a dissociated state. CO3 + H = HCO3. At the water/rock interface the physical solution of calcite occurs by freeing ions from a crystal lattice. In the presence of water the dissociated atoms combine to form calcium and carbonic acid (Fig. 3).

FIGURE 3.

The Dissolution of CaCO3 and the Mutual Dependencies in the System



$CaCO_3 = Ca + CO_3$. $CaCO_3 + CO_2 + H_2O = Ca + 2HCO_3$. The dissolution of $CaCO_3$ is greatly increased by the presence of protons. Protons indicate the acidity of water and regulate the dissolution rate (Jennings 1985).

CAVE DEVELOPMENT

The progressive development of an underground cavity is encouraged by the diversion of surface water flow and the integration of subsurface water flow. The zone of water flow in underground passages migrates progressively downward into the rock mass. The downcutting occurs when the base level of the surface system is lowered. The subsurface passages that are water filled are called phreatic passages. As the passage flow becomes more stream like with an air space above, the water flows under vadose conditions.

The first phase of cavity formation involves phreatic water flow. A) The phreatic flow region is the zone of saturated flow. This region is subsurface and is controlled by the porosity and permeability of the rock. B) The permeability of the rock is due to subcapillary and capillary interstices. These interstices will transmit water through rock if the pressure gradient produced by the water column is sufficient for seepage. In capillary interstices the water travels 10 - 100 meters per year, exemplifying that this first phase of underground karstification is time consuming.

Open interstices are more efficient water bearing channels. The water moves in sinuous crisscrossed courses in the interstices. Heavier flow widens the interstice and causes less discharge from the neighboring water courses. When there are water courses of similar value they all grow to become cave passages that are interconnected. In this period the future passage network is formed as one or a few water courses become dominant and others are abandoned in disuse. When the direction of flow to the local baselevel runs almost parallel to the strike, these water courses are on one bedding plane.

For capillary interstices to become passable for water, phreatic conditions must dominate. These conditions are favorable for corrosion by mixing waters. This takes place by means of joints, for foreign water must be introduced on the bedding plane. When joints cut the bedding plane a mixture results and hence corrosion. These expand the interstice in the direction of outflow. The probability of corrosion is greatest near the surface of the karst water body. Therefore, the shallow phreatic zone is favored for the formation of cave passages.

Phreatic water flow

Phreatic passages are water filled passages that tend to be circular or elliptical in crossection, enabling solutional attack on all surfaces. Slow flow permits interweaving routes to be used simultaneously. As solution widens the passage there is sufficient head to drive the water through at normal river speeds. As the passage enlarges the frictional loss of energy at the rock faces reduces and is smaller in relation to total frictional drag. This causes the velocity to increase. As the velocity increases, mass transfer of solute from the surface is enhanced which further enlarges the passage. These conduits play a greater part in water movement the larger they become. These passages do not follow the most direct route to the outflow, they follow the more efficient route. Efficiency of a route is generally determined by the size of the preferred opening at the beginning (Palmer 1984).

Network caverns are the key forms of the phreatic zone. Bedding plane passages form the phreatic zone. Symmetrical, elliptical, and lenticular cross sections compose the phreatic zone plus the high water area of the vadose zone and larger siphons. Inverse potholes from corrasion due to mixing waters are a sign of phreatic conditions. Descents and ascents alternating in a passage and hydraulically formed passage ceilings are also signs that phreatic conditions were present during cave formation (Bretz 1942).

Baselevel of Local Hydrology

Passage sections grow until they reach the breaking limit of the rock. Beyond this limit the breakdown (incasion) dominates the shaping of the cave. The shape of Mammoth Cave in Kentucky is incasion dominated. Changes in the local baselevel causes the development of new underground passage levels. When breakdown in cave passages occur, the depressurization in the passage leads to a loss in pressure height, or pressure head. This loss can be compensated for by an increased hydraulic head or by a strong high water zone. A deeper system of passages is established in the zone of the new baselevel (Bogli 1980).

Vadose Water Flow

Primary vadose caves are formed when water flowing in the underground has an open water surface and moves pressure free in a gravitational channel. Passages in the vadose channel descend continuously. The primary vadose cave formation may occur without previous phreatic conditions characterized by straight little branching courses. These branches do not form a network and they have a uniform gradient. The passages are narrow, high, and are frequently steep and shaft-formed. The passages of the primary vadose type are rare. Primary vadose caves are simpler systems containing some branches. Interconnected branches are accidental. The passages of primary vadose caves follow open joints. Commonly the passages formed are high and narrow with the shape of open joints and canyons. Primary vadose caves have a uniform gradient without rocky ascents which oppose the general attitude to the strata.

Secondary vadose caves have a preceding phreatic phase. The deepest possible passage in the network is the discharge conduit. Many of the other passages become dry and inactive. The ascents from the phreatic phase are still evident. The passages cross sections have the old phreatic shape and the vadose canyons cut into the floor of the same passage. Canyons form in the passages with broad, flat floors and slight inclined meanders are often present. Mammoth Cave Kentucky is a secondary vadose cave. Deepening of the conduits in the direction of flow is common.

CONCLUSION

The various phases of cave development have been classified by Alfred Bogli. The following is the Bogli Organization of Cave Development (Bogli 1980).

A) Previous Phase: the rock persists in the given state--its cavities are water-filled and nothing changes.

B) Initial Phase: the local baselevel has reached such a position that a pressure gradient is created in the rock interstices. The water moves so that the widening of the interstices begins--Predominant corrosion by mixing waters, phreatic zone.

C) Youth: water flows faster--erosion joins corrosion--underground cavities develop to a relatively large size cavity, bumps occur but other forms of breakdown are lacking, flow is mostly phreatic.

D) Maturity: crossections continue to increase until the first signs of incasion with occasional ceiling breakdown--phreatic and/or vadose (high water zone, feeders, may be inactive).

E) Old Age: incasion, especially ceiling breakdown. Covering and destruction of the forms of maturity, ficticious joint passages appear with vadose flow, rarely phreatic inactive cave development.

F) Senility: cave becomes destroyed.

The development of underground cavities called caves is due to the hydrologic cycles affecting karst terrains. However, the subsurface behavior of the water and its influence on the character of the rock makes cave development a specialized area of study. When surface water flows over a terrain and is in contact with the ground, some of that water will penetrate the upper surface of the ground. When this underground seepage begins all interstices and open joints fill up with water and there is no pressure gradient affecting the system. As the local baselevel becomes deeper a pressure gradient is slowly created. The water moves slowly at first and then with increasing volume. This type of flow is deep phreatic flow and solutional pits and passages begin to form. The water in the saturation zone sinks until it comes close to the local baselevel. This causes the karst forming processes to move into the deep phreatic zone. At a point the sinking karst water level will begin to cease and this is where karstification reaches its maximum. As the local baselevel deepens, the phase of karstification, the phase in which the water dissolves the rock and forms pits and passages, will be revived (Bogli 1980).

As the passages and conduits become larger and the volume of water transported through them increase the chance of deposition increases. This deposition can be from chemical precipitation or by incasion. Cave features are controlled by the behavior of the water and the hydrologic characteristics of the rock and the characteristics of the features formed due to the interaction between the water and the rock. The formation and development of these underground cavities is also governed by external features such as hydraulic gradient, climate, and stratigraphy.

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